Encyclopedia of Earthquake Engineering
DOI 10.1007/978-3-642-36197-5_29-2

Archaeoseismology

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Synonyms

Archaeological seismicity; Earthquake archaeology; Seismic archaeology

Introduction

In 1991 an international conference was held in Athens (Greece), marking the beginning of the modern research field of **archaeoseismology**, described as *"the study of ancient earthquakes from the complementary standpoints of their social, cultural, historical and physical effect"* (Stiros and Jones 1996). Besides the term archaeoseismology, also the term **seismic archaeology** was introduced to emphasize the use of archaeological methods in the quest to better understand the effects of earthquakes on historical buildings and archaeological remains. Moreover, in analogy with historical seismicity, also the term **archaeological seismicity** was suggested.

Archaeoseismology can thus be defined as **the interdisciplinary study of ancient earthquakes through evidence in the archaeological record, such as destruction layers, structural damage to man-made constructions, cultural piercing features, indications of repairs, abandonment, cultural changes, etc**. Archaeoseismology is thus seen as a subdiscipline of paleoseismology with a particular focus on man-made constructions as a potential source of paleoseismological information covering the last few millennia. By doing so, archaeoseismology serves objectives proper to seismology and earthquake geology, i.e., parameterizing of earthquakes in an effort to assess the seismic hazard in a region.

Earthquake archaeology can be considered as a synonym for archaeoseismology. But earthquake archaeology can also be seen to serve objectives proper to archaeology, i.e., reconstructing human history, in particular attempting to better understand the true impact of earthquakes on human history. The term earthquake archaeology can be traced to the Japanese term *jishin kōkogaku*, referring to a research field developed in the mid-1980s in Japan primarily through the initiative of Sangawa Akira, a geomorphologist at the Geological Survey of Japan, focusing on sediment deformation features within archaeological contexts (Barnes 2010).

Since the book *Archaeoseismology* (Stiros and Jones 1996), a series of special issues of journals has reflected the evolution of the burgeoning discipline over the last two decades towards an ever increasing multidisciplinary discipline (McGuire et al. 2000; Galadini et al. 2006a; Caputo and Pavlides 2008; Sintubin et al. 2010; Silva et al. 2011).

In the current entry, **archaeoseismology** is considered as a discipline belonging to the broad research realm of **earthquake sciences**, reflected by a continuum of overlapping and complementary research fields, each focusing a particular source of earthquake data, applying appropriate methods and techniques, and targeting a specific time window. In this respect, archaeoseismology

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DOI 10.1007/978-3-642-36197-5_29-2

bridges the gap between **instrumental** and **historical seismology** on the one side and **paleoseismology** and **earthquake geology** on the other. Archaeoseismology focuses on cultural material data spanning the last few millennia. It shares, however, a common goal with the other disciplines, i.e., a better understanding of the earthquake history within a region in an attempt to assess the seismic hazard and mitigate the seismic risk. Most valuable contribution of archaeoseismology to seismic hazard assessment is situated in earthquake-prone regions with a long and lasting cultural heritage. Seismic-hazard practitioners are confronted with the problem that the instrumental record is too short (only spanning somewhat over a century) and the historical record too incomplete or even inexistent. By having the potential of determining earthquake activity over millennial time spans, archaeoseismology can indeed extend the archive of earthquakes beyond written sources, thus becoming a legitimate and complementary source of seismic-hazard information.

After a short historical note, a summary of the different types of archaeological evidence for ancient earthquakes, commonly used in archaeoseismology, is given. Subsequently, the strengths, challenges, and pitfalls of archaeoseismology are discussed. Some new developments in archaeoseismology will be introduced. In conclusion, some issues and perspectives in archaeoseismology are presented.

A Historical Note

In the first volume of the *Palace of Minos*, published in 1921 (Evans 1921), Sir Arthur Evans did not mention earthquakes as a possible cause for the destructions observed during excavation works at the Bronze Age, Minoan site of Knossos (Crete, Greece). In the second volume of the *Palace of Minos*, published in 1928 (Evans 1928), though, tectonic earthquakes became the primary destructive agent, not only leaving a clear marker horizons in the archaeological stratigraphy but also causing cultural change as evidenced by discontinuities in ceramic style and architecture. So, what happened in those 7 years that completely changed Evans' thinking?

On 20 April 1922, during the excavation of the *"House of the Sacrificed Oxen"* and the *"House of the Fallen Blocks"* (Fig. 1) at Knossos, Evans experienced an earthquake, leading him to believe that earthquakes of tectonic nature (so not related to the volcanic activity of the Thera/Santorini volcano) may very well have caused damage to the Minoan buildings during the Bronze Age. But only after experiencing the dramatic earthquake that hit the Eastern Mediterranean on 26 June 1926 and caused severe damage in the region of Heraklion, Sir Arthur Evans got convinced that earthquakes are the primary destructive agent responsible for the main stages of destruction observed at Knossos. He developed a seismic archaeological stratigraphy, marked with a number of earthquake-related destruction horizons (cf. Jusseret and Sintubin 2013). This work of Sir Arthur Evans can thus indeed be seen as the earliest attempt to introduce earthquakes into archaeological contexts.

Evans' ideas inspired a number of his colleagues around the Eastern Mediterranean, in particular Claude Schaeffer, excavator of the Bronze Age sites of Ugarit (Syria) and Enkomi (Cyprus). In his book *Stratigraphie Comparée et Chronologie de l'Asie Occidentale*, published in 1948 (Schaeffer 1948), Claude Schaeffer went even one step further by correlating archaeological destruction layers attributed to earthquakes between Bronze Age archaeological sites throughout the Asia Minor, the Caucasus, and the Middle East, setting the stage for the myths of regional earthquake catastrophes. Incorporating modern concepts of seismic storms, the myth of the Late Bronze Age seismic paroxysm around 1200 BC endured to date (e.g., Nur and Cline 2000).

DOI 10.1007/978-3-642-36197-5_29-2

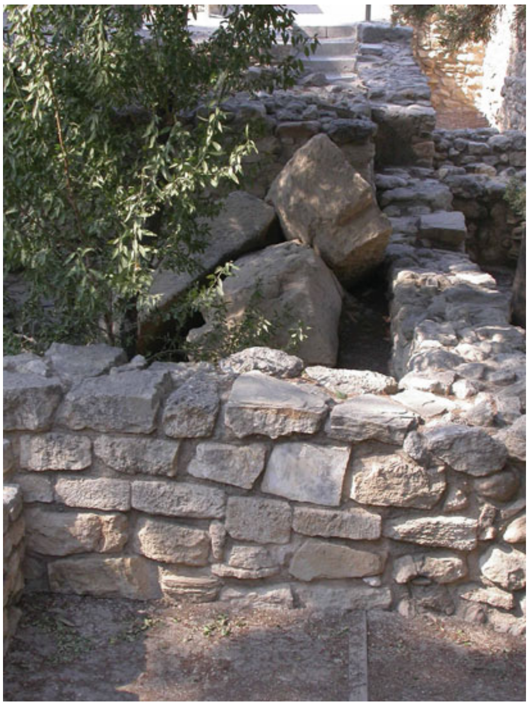

Fig. 1 The *"House of the Fallen Blocks"* at Knossos, of which the particular context of the massive blocks inspired Sir Arthur Evans that a major earthquake may have been responsible for this damage (cf. Sintubin 2011) © Sintubin

Ever since, earthquakes became all too easy a "deus ex machina" to explain to otherwise inexplicable at archaeological sites, eventually even to add drama to a site's history. While skeptical earthquake scientists portrayed this indiscriminate use of earthquakes as neocatastrophism, advocates see the earthquake hypothesis as the simplest solution, referring to Occam's razor. Therefore, many earthquake scientists still question the basic principles and practices of archaeoseismology.

Ancient Earthquakes

Earthquakes that form the subject of archaeoseismology are defined as **ancient earthquakes**, i.e., pre-instrumental earthquakes that can only be identified through indirect evidence in the archaeological record (e.g., Sagalassos earthquake; cf. Similox-Tohon et al. 2005). Earthquakes that are documented in the historical record may be included if they left marks in the archaeological record.

Earthquakes can basically be subdivided in **instrumental** and **pre-** or **noninstrumental**; the former are instrumentally recorded by seismometers, while the latter are indirectly recorded. The instrumental record covers a little more than a century since the first modern seismometers were designed in the 1890s.

Of **instrumentally recorded earthquakes**, all physical parameters (e.g., magnitude, seismic source, epicenter, duration, intensity distribution, sequence of aftershocks) can be derived. These earthquakes are the main subject of **seismology**. Recent earthquakes can have a major impact on cultural heritage (e.g., 2003 Bam M_W 6.6 earthquake), historical buildings (e.g., 2009 L'Aquila M_W 6.3 earthquake), and/or archaeological remains. The latter earthquakes, affecting archaeological remains, are though excluded from the field of archaeoseismology.

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Pre-or **noninstrumental earthquakes** are only indirectly recorded, in the historical, archaeological, and/or geological record. Earthquake parameters that can be derived from these records concern macroseismological parameters, such as intensity, macroseismic epicenter, date, etc.

Historical earthquakes are pre-instrumental earthquakes of which information can be found in all types of historical – written – records (e.g., reports, epigraphy, epitaphs). All this historical information is compiled into earthquake catalogues. Archaeoseismology can complement the knowledge with respect to historical earthquakes, when the evidence of specific, well-documented, historical earthquakes (e.g., 365 AD Crete earthquake) on archaeological sites is searched for. Also, paleoseismology can add information to better constrain the macroseismological parameters of historical earthquakes.

Prehistorical earthquakes are earthquakes that have no historical record. They can both be ancient earthquakes or paleo-earthquakes.

Paleo-earthquakes, finally, can be interpreted widely, incorporating all prehistorical earthquakes, and even historical earthquakes. In this respect, it becomes synonymous to pre-instrumental earthquakes. One can opt to narrow down the definition of paleo-earthquakes to earthquakes of which evidence is only found in the geological and/or geomorphological record, being subject of **paleoseismology**. These earthquakes are also called **fossil earthquakes**.

Archaeological Evidence for Ancient Earthquakes

Archaeoseismology calls upon archaeological material, ranging from a single occupation horizon within a Holocene stratigraphical context (e.g., Tuttle and Schweig 1995) to a widespread archaeological site with monumental buildings (e.g., Similox-Tohon et al. 2006). Methodological developments in archaeoseismology is indeed primarily grafted on archaeological work in the Eastern Mediterranean and the Middle East, which depends strongly on identifying structural damage to monumental buildings and other cultural remains at archaeological sites (e.g., Stiros 1996).

There are two limiting factors to archaeoseismological investigations. The first is related to temporal aspects of the archaeological record. On the one hand, the time span of occupancy of a site largely determines the archaeoseismological potential of a site (cf. Sintubin and Stewart 2008). It is obvious that the longer the site's occupancy, the higher chances are that a major earthquake has affected the site and left its marks in the archaeological record. On the other hand, the archaeological record is not evenly distributed through time, to a large extent dependent on socioeconomic, political, and cultural conditions of an ancient society. Secondly, archaeoseismological work is limited to archaeological sites, which are commonly rather a rare occurrence. There is though a remarkable spatial bias advantageous to archaeoseismology, due to a *"fatal attraction"* (Jackson 2006). On the one hand, there appears to be a close relationship between tectonically active environments – thus prone to earthquakes – and ancient civilizations along the southern boundary of the Eurasian Plate (Force and McFadgen 2010). On the other hand, many settlements are founded in seismic landscapes (Michetti and Hancock 1997), thus in the direct proximity of active earthquake faults, as convincingly illustrated by numerous archaeological sites throughout the Mediterranean and the Middle East. **Seismic landscapes** are defined as the cumulative geomorphological and stratigraphical effect of signs left on the environment by its past earthquakes over a geologically recent time interval (Michetti and Hancock 1997).

The archaeological record can be used in basically three ways to help confront the seismic-hazard threat. First, where archaeological relics are displaced, they can be used to find active faults, show in which direction faults slipped during the earthquake(s), and establish comparative fault-slip rates.

DOI 10.1007/978-3-642-36197-5_29-2

Second, archaeological evidence can date episodes of faulting and shaking. Third, ancient signs of earthquake-related damage, commonly related to ground shaking or ground instabilities (e.g., liquefaction), can be searched for.

Structural Damage Due to Surface Rupturing or Ground Failure

The most obvious and straightforward archaeological evidence of fault activity – and thus of earthquakes – are archaeological remains that are partly displaced due to coseismic surface rupturing on an active fault. As already mentioned, it is definitively not a coincidence that archaeological sites are astride active faults.

As cultural piercing features, these **faulted relics** not only serve to identify active faults, but they are also used to determine the type of faulting (normal, reverse, strike slip), the amount of coseismic slip related to a single earthquake, as well as the cumulative fault slip. All these data eventually allow to derive time-averaged fault-slip rates over time spans of centuries to millennia, very comparable to paleoseismological work. The fault-slip rates obtained from an archaeological context can subsequently be compared to long-term slip rates from paleoseismological work, enabling the evaluation of potential slip deficits and thus increased seismic hazards.

The most spectacular cases of such faulted relics can be found astride strike-slip faults, in which case there can be no doubt of the tectonic nature of the displacement. Notorious examples are the Crusader Fortress of Vadum Iacob (Israel) (Fig. 2) (cf. Marco et al. 1997) and the Al Harif Roman aqueduct (Syria) (cf. Sbeinati et al. 2010), both located astride the Dead Sea fault, a left-lateral transform plate boundary between the African and Arabian plates. By the way, as long, linear

Fig. 2 The wall of the *Crusader Fortress of Vadum Iacob* (Ateret, Israel) (cf. Marco et al. 1997) is displaced *left* laterally over more than 2 m. The fortress has been built astride the Dead Sea transform plate boundary between the African and Arabian plates © Sintubin

DOI 10.1007/978-3-642-36197-5_29-2

Fig. 3 The mosaic floor of the Roman *Neon Library at Sagalassos* (SW Turkey) has been cut by a normal fault, of which a post-363 AD activity (terminus post quem) can be inferred based on the archaeological evidence (cf. Similox-Tohon et al. 2006) © Sintubin

structures, aqueducts are ideal cultural piercing features because chances are they cross more than one fault. Also in extensional settings, giving rise to the typical seismic landscapes of the Mediterranean (from Turkey to Spain), faulted relics are often encountered in archaeological sites (Fig. 3) (e.g., Similox-Tohon et al. 2006). In these cases of dip-slip, normal-fault movements, particular caution should be paid to preclude gravitational mass movement that may or may not be seismically triggered (ground failure). Complementary and independent, usually paleoseismological and/or geophysical, evidence to support a tectonic nature of the normal displacement, observed in the faulted relics, is therefore imperative (e.g., Similox-Tohon et al. 2005).

Besides these on-fault effects, numerous off-fault, coseismic ground-failure features can find their way into the archaeological record, such as landslides and rockfalls, subsidence and uplift, and liquefaction (see Rodríguez-Pascua et al. 2011 and references therein). The latter sediment-deformation features form the focus of earthquake archaeology Japan style (Barnes 2010).

Archaeological Destruction Horizons

An **archaeological destruction horizon** (destruction layer/destruction deposit) designates a horizon in the archaeological stratigraphy showing evidence of sudden destruction caused by human (e.g., war, vandalism) and/or natural agents (e.g., earthquake, storm, flood). These destruction horizons commonly occur on top of "living surfaces," evidenced by, e.g., in situ broken vases (Fig. 4), buried valuable objects, and/or skeletons of victims. Other criteria are, e.g., burned material, charcoal, collapsed architectural debris, and crushed, toppled objects.

DOI 10.1007/978-3-642-36197-5_29-2

Fig. 4 In situ broken vessels, evidencing a collapse on a "living surface," as part of a destruction horizon at the Minoan site of *Sissi* (Crete) that has been attributed to an earthquake in the thirteenth century BC (cf. Jusseret and Sintubin 2012) © J. Driessen

The use of destruction horizons in archaeoseismology goes back to the original work of Sir Arthur Evans in Minoan Knossos (Bronze Age Crete), inspiring several generations of archaeologists who, often too easily ("deus ex machina"), attributed destruction horizons to catastrophic earthquakes. Identifying the true agent, eventually responsible for the destruction horizon, is rarely clear and unambiguous and remains one of the major challenges of archaeoseismology.

Destruction horizons, which can with a high degree of certainty be related to ground failure and/or ground shaking caused by an earthquake, are the most appropriate "proxies" for ancient earthquakes in archaeological contexts dominated by rubble architecture and associated stratigraphy, such as the Bronze Age civilizations around the Mediterranean and the Harappan civilization in the Indus Valley. In these contexts, no appeal can indeed be made to structural damage evidence on monumental buildings and constructions.

Besides evidencing ancient earthquakes, material (e.g., charcoal) and artifacts (e.g., ceramics, coins) included in the destruction horizons can be used to date episodes of earthquake damage, by means of, e.g., radiocarbon dating, changes in ceramic styles, and numismatics. A major drawback is the temporal resolution of these dating methods with uncertainties ranging from decennia to centuries. On the one hand, this does not allow to pinpoint a destruction horizon to a specific historical earthquake. On the other hand, imprecise age control leads to discrete multiple earthquakes, among which the aftershock sequence of a major earthquake, being amalgamated to "oversized" earthquake catastrophes. Finally, weak time constraints on destruction horizons hamper any reliable territorial correlation of destruction horizons between archaeological sites, again giving rise to the danger of amalgamating regionally distinct earthquakes.

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Fig. 5 Recycling of building material in repair works of a wall at *Susita* (Golan Heights) (cf. Sintubin 2011), possibly after a destructive earthquake © Sintubin

Other issues concerning destruction horizons are preservation and disturbance. Little is known about the way ancient societies coped with the aftermath of a major earthquake. Earthquake debris may have been cleared from streets and buildings and disposed at particular dumpsites, so that the earthquake destruction horizon is no longer preserved in the archaeological record. Valuables and/or victims may have been recovered from the debris, while material may have been reused in rebuilding, leaving behind a highly disturbed earthquake destruction horizon. It is therefore fair to conclude that the visibility of earthquake destruction in the archaeological stratigraphy is rather dependent on social factors than on physical parameters (cf. Jusseret and Sintubin 2012).

Finally, other archaeological evidences, such as repairs, recycling of building materials (Fig. 5), complete or partial abandonment, and architectural and/or cultural changes, can further contribute to the identification of ancient earthquakes.

Structural Damage Due to Ground Shaking and Ground Motion

A third type of earthquake evidence in the archaeological record are typical **strain structures in the building fabric** that are primarily caused by coseismic ground shaking and ground motion. These earthquake-related damage features are most conspicuous on monumental buildings and constructions, such as temples, fountains, theaters, basilicas, pavements, columns, statues, aqueducts, etc.

A first systematic inventory of possible earthquake-related damage typologies has been introduced by Stiros (1996). Currently all these potential earthquake indicators are compiled in a comprehensive classification of **Earthquake Archaeological Effects** (EAEs) (Rodríguez-Pascua et al. 2011), completely based on the guidelines of the Earthquake Environmental Effects (EEEs) that are used in the framework of the macroseismic Environmental Seismic Intensity scale (ESI2007,

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Fig. 6 Displaced drums of a column in the *Temple of Aphrodite* in the Roman city of *Aphrodisias* (SW Turkey), as a potential earthquake archaeological effect © Sintubin

Michetti et al. 2007). These guidelines prescribe the difference between "primary (direct) effects" and "secondary (indirect) effects." In archaeological contexts, the latter effects of which evidence can be found in the archaeological record and in particular destruction horizons, reflect the way an ancient community copes with the consequences of an earthquake affecting their settlement. Besides the on-fault (e.g., surface rupturing) and off-fault (e.g., liquefaction) geological effects, the former effects are specifically recorded in strain structures in the building fabric.

Different types of strain structures can, on the one hand, be generated by coseismic ground motion: folded and fractured pavement; shock breakouts in flagstone pavement; tilted, rotated, displaced, and bent walls, etc. On the other hand, other types of strain structures in the building fabric can be generated by coseismic ground shaking: penetrative fractures in masonry walls and columns; rotated, displaced, and ejected masonry blocks in walls; rotated and displaced drums in columns (Fig. 6); dropped keystones in arches (Fig. 7); rotated steps in stairways; collapsed stairways; folded curbs; domino-type collapsed walls and columns; directional collapse of columns; collapsed vaults; impact markings on pavements; dipping broken corners and chipping marks; U-shaped gaps in walls, etc.

The obvious difficulty with these building fabric effects is that it remains very challenging to distinguish between damage caused by an earthquake and damage caused by other destructive physical or human agents, such as natural failure of the foundations, vandalism, or warfare. Moreover, standing or partially standing buildings and constructions at archaeological sites in earthquake-prone regions most probably experienced ground shaking from numerous – minor to moderate to major – earthquakes over the life span of the structure, which makes it nearly impossible to attribute specific building fabric effects to a particular earthquake. Working with these damage

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Fig. 7 A dropped keystone in the *Roman Baths at Sagalassos* (SW Turkey), interpreted as a potential earthquake archaeological effect (cf. Similox-Tohon et al. 2006) © Sintubin

typologies, possibly indicative of ground shaking, the investigator has to be very cautious not to "overinterpret" the potential earthquake archaeological effects. Uncertainties, inherent to any archaeologically based earthquake hypothesis, should moreover be assessed properly (cf. Sintubin and Stewart 2008).

Parameterization of Ancient Earthquakes

Besides the inherent ambiguities and uncertainties of archaeological earthquake evidence, primarily resulting from the difficulty to irrefutably distinguish between damage caused by earthquakes and that caused by other natural agents or human intervention, the main issue archaeoseismology is confronted with is the question how earthquake evidence in destruction horizons and/or disturbed buildings can be meaningfully translated into physical earthquake parameters, such as intensity, magnitude, distance to epicenter, date of earthquake, ground acceleration, etc. Ultimately, because the limitations of the archaeoseismological record are all too obvious when it comes to claiming its potential role in seismic-hazard studies, it all boils down to the question what the true added value is of archaeoseismology.

In Search of a Shared Protocol and Standardized Methodology

Archaeoseismology's greatest challenge – and its foremost attraction – remains to date the integration of principles and practices of a very wide range of sciences, from history, anthropology, archaeology and sociology, over geology, geomorphology, geophysics, and seismology to

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DOI 10.1007/978-3-642-36197-5_29-2

architecture and structural engineering. Arguably the principle difficulty in archaeoseismology is the lack of a shared protocol and of a rigorous and transparent standardized methodology (cf. Sintubin and Stewart 2008 and references therein).

Through the years, different, primarily qualitative, archaeoseismological schemes have been proposed, consisting of points of interest (Karcz and Kafri 1978; Rapp 1986; Nikonov 1988; Stiros 1996), key research questions (Guidoboni 1996), or flow charts (Galadini et al. 2006b) that ought to be considered during excavation works at an archaeological site by collaborative teams of seismologists, geologists, archaeologists, etc. (see Sintubin and Stewart 2008 for synthetic overview of archaeoseismological schemes). More recently, the comprehensive classification of earthquake archaeological effects (EAEs) (Rodríguez-Pascua et al. 2011) pursues the integration of archaeoseismological evidence in the framework of the macroseismic Environmental Seismic Intensity scale (ESI2007, Michetti et al. 2007). These efforts to develop a shared protocol, however, are commonly designed from within a single scientific discipline.

Most of these schemes have been grafted onto the archaeological work in the Mediterranean and the Middle East, strongly relying on strain structures in the building fabric (e.g., Stiros 1996). More quantitative approaches evaluate the probability of the occurrence of a proposed ancient earthquake by using a feasibility matrix for archaeoseismological findings (Hinzen 2005) or assess the degree of certainty to which an archaeological site has recorded an ancient earthquake by using a logic-tree formalism (Sintubin and Stewart 2008).

In recent years, a clear shift in perspective, from qualitative to more quantitative and multidisciplinary approaches, trying to integrate earthquake evidence from different perspectives (e.g., archaeoseismology, geophysics, paleoseismology, geomorphology, geology), has definitively proven a major advancement in the discipline, supporting the reliability of the archaeoseismological evidence (e.g., Similox-Tohon et al. 2006).

Because of the wide variety of disciplines involved, from the humanities and the social, natural, and engineering sciences, it seems, though, nearly inevitable that all practitioners who look at earthquake evidence in the archaeological record will keep pursuing different objectives. The historian may want to know if an earthquake had any effect on the political, social, or military balance in a region. The engineer may be concerned about mitigating the seismic threat to our cultural and architectural heritage, while the seismologists are attempting to complete the historical catalogue of earthquakes and their physical parameters. Finding a balance between all these interests will also in the future remain archaeoseismology’s greatest challenge.

Ancient Seismoscopes

For assessing the seismic hazard of a region, an accurate catalogue of earthquakes and their physical parameters is imperative. Seismic-hazard practitioners need exact dates, magnitudes, source areas, etc. of past earthquakes. Taking into account the incompleteness of the archaeological record, its limited spatial and temporal resolution, and the uncertainties inherent to archaeological earthquake evidence, the skepticism with respect to the applicability of archaeoseismology in **seismic-hazard studies** is indeed legitimate (cf. Sintubin 2011).

Some common pitfalls keep adding to the seismologist’s skepticism. There is the **preservation problem**. The archaeological record is not evenly distributed through time. Ancient history consists of long periods of cultural, social, and political stability and flourishing economies, during which any sign of earthquake is most probably expertly covered up. In contrast, during intervening, short periods of social and political upheaval, and economic crisis, signs of destructive earthquakes may be left extant, primarily because there is no impetus or funds to fully recover from the earthquake

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disaster. Only then, the earthquake leaves it marks in the archaeological record, giving rise to an observational bias that focuses on periods of upheaval, destruction, abandonment, etc.

Another danger exists that "anomalous" earthquake catastrophes, supposedly proven by archaeologists, are used uncritically in seismic-hazard assessments as "real" events (Ambraseys et al. 2002). Moreover, confronting the archaeoseismological evidence, commonly poorly constrained in time and space, with the evenly incomplete and sometimes poorly constrained historical earthquake catalogues, may carry the risk of an arbitrary correlation, inevitably leading to **circular reasoning** (Rucker and Niemi 2010). When archaeologists identify a destruction horizon as caused by an earthquake and consult existing earthquake catalogues to assign a date to the particular earthquake-related destruction horizon, the risk exists that historical seismologists add this particular archaeological site to the catalogue as evidence for that particular historical earthquake. This overreliance on historical catalogues clearly corrupts the usefulness of archaeoseismology and should therefore be omitted from archaeoseismological practices.

Given all these pitfalls, it becomes apparent that archaeoseismological investigations should indeed not start from a seismological perspective but from the archaeological earthquake evidence itself, with all its inherent limitations and uncertainties. Rather than simply complementing earthquake catalogues with potentially highly conjectural, ancient earthquakes, archaeological sites may have the potential of becoming testing grounds to quantitatively assess site-specific ground effects. In this respect, archaeological sites become **ancient seismoscopes** that can be used strategically to examine specific earthquake scenarios in a region (cf. Sintubin 2011). Archaeological sites, especially those with a long and lasting history, do have the potential to have recorded the effects of a major earthquake. A quantitative assessment of the ground motions on archaeological sites may indeed hold the eventuality to have narrowed down macroseismic parameters associated with the maximum credible earthquake in the region, irrespective of the time of occurrence, the magnitude, the seismic source, etc. With such an approach, archaeoseismology enters in the logics of scenario-based, deterministic seismic risk assessment.

New Developments in Archaeoseismology

This tendency towards a more standardized and quantitative approach of potential archaeological earthquake evidence in archaeological sites is fully exemplified in the rapid advances in **quantitative archaeoseismology** (cf. Hinzen et al. 2011 and references therein). This recent development in archaeoseismology primarily focuses on monumental architecture, the classical field of application of archaeoseismology since its beginning (cf. Stiros 1996). Quantitative archaeoseismology firstly applies modern techniques, such as 3D laser scanning (e.g., ground-based LIDAR), to obtain a three-dimensional structural model of the archaeological damaged building or structure, allowing the construction of a very precise structural damage inventory. Using earthquake engineering models, the dynamic behavior of the ancient structure can be evaluated. Subsequently, scenario-based earthquake ground motion simulations enable testing a realistic earthquake hypothesis to explain the damage observed. This approach has already lead to the conclusion that in a number of cases, alternative, natural, or anthropogenic causes are more probable than the seismic cause that has originally been considered. Moreover, "classical" damage typologies attributed to earthquake-related ground motions, such as the perfectly aligned toppled columns (Fig. 8), could not be validated, even adding to the skepticism towards "classical" archaeoseismological practices.

Besides this added value of quantitative archaeoseismology with respect to monumental architecture, also the value of rubble architecture and associated destruction horizons get again particular interest in a more quantitative, **integrated territorial approach** that starts from the specific seismotectonic context and the empirical ground-motion relationships of potential earthquake

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Fig. 8 Perfectly aligned *toppled columns* at *Susita* (Golan Heights), classically interpreted as indicative for the direction of strong ground motion caused by a major earthquake. Such earthquake hypothesis does not pass the test of scenario-based ground motion simulations (cf. Hinzen et al. 2011) © Sintubin

sources and focuses on well-documented, high-visibility archaeological contexts, characterized by very rapid ceramic change (~100-year time window) (cf. Jusseret and Sintubin 2012).

Issues and Perspectives in Archaeoseismology

Archaeoseismology will always be plagued by the ambiguities inherent to the archaeological record of ancient earthquakes. In this respect, archaeoseismology may very well never be able to deliver reliable and conclusive earthquake evidence that is needed to improve the **assessment of the seismic hazard** in a region. New developments towards more integrated, multidisciplinary approaches as well as quantitative archaeoseismology will allow, though, that the potential of archaeological sites as **ancient seismoscopes** is fully developed in the future.

The fact that the archaeological visibility of earthquakes may be strongly biased towards the relatively short but commonly well-documented (e.g., rapid changes in ceramic styles) periods in a society's history of social, political, and/or economic turmoil opens unique perspectives for archaeoseismological research. Preservation of archaeological earthquake evidence may indeed rather be related to societal factors than to physical aspects of the ancient earthquakes. Ultimately, the relatively undisturbed, extant archaeological record of earthquakes can tell us more about past societies and their attitude to physical disasters (cf. Jusseret and Sintubin 2012). A better appreciation of the complex way by which our ancestors responded to damaging earthquakes might indeed shed light on the societal factors defining the resilience or vulnerability of past societies. Eventually, by highlighting how our ancestors coped with earthquake disasters, archaeoseismology could find new aspirations in establishing local **earthquake cultures** in earthquake-prone regions (cf. Sintubin et al. 2008), possibly providing a substantial contribution to the **mitigation of the earthquake risk**, by improving earthquake risk literacy and awareness.

Summary

Archaeoseismology is the interdisciplinary study of pre-instrumental, **ancient earthquakes** through indirect evidence in the archaeological record. As a burgeoning discipline within the broad research realm of **earthquake sciences**, archaeoseismology bridges the gap between **instrumental** and **historical seismology** on the one side and **paleoseismology** and **earthquake geology** on the other.

The archaeological record can be used in basically three ways in the identification and characterization of ancient earthquakes. The most obvious and straightforward archaeological evidence of fault activity are archaeological remains that are partly displaced due to coseismic surface rupturing on an active fault. As cultural piercing features, these **faulted relics** can be used to determine the type of faulting, the amount of coseismic slip, as well as the cumulative fault slip. Within the archaeological stratigraphy, particular horizons can be designated to sudden destruction caused by human and/or natural agents. If the **archaeological destruction horizons** can be attributed to an earthquake with a high degree of certainty, material included in the destruction horizons can be used to date episodes of earthquake damage. Destruction horizons are the most useful "proxy" for ancient earthquakes in archaeological contexts dominated by rubble architecture and associated stratigraphy. A third type of earthquake evidence in the archaeological record are typical **strain structures in the building fabric** that are primarily caused by coseismic ground shaking and ground motion. These earthquake-related damage features are most conspicuous on monumental buildings and man-made constructions.

Archaeoseismology will always be plagued by the ambiguities and uncertainties inherent to the archaeological earthquake evidence, primarily resulting from the difficulty to irrefutably distinguish between damage caused by earthquakes and that caused by other natural or human agents. In this respect, archaeoseismology may very well never be able to deliver reliable and conclusive earthquake evidence that is needed to improve the assessment of the seismic hazard in a region. Archaeological sites have though the potential of becoming testing grounds to quantitatively assess site-specific ground effects. As **ancient seismoscopes**, archaeological sites may hold the eventuality to have narrowed down macroseismic parameters associated with the maximum credible earthquake, irrespective of the time of occurrence and the physical parameters of the earthquake. Finally, preservation of archaeological earthquake evidence may rather be related to societal factors than to physical parameters. In this respect, the relatively undisturbed archaeological record of ancient earthquakes can tell us more about past societies and their attitude to physical disasters.

Cross-References

- ► Collapse Prediction of Structures Under Seismic Action
- ► Damage to Ancient Buildings from Earthquakes
- ► Damage to Buildings: Modeling
- ► Deterministic Seismic Hazard Analysis
- ► Earthquake Location
- ► Earthquake Magnitude Estimation

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- ▶ Earthquake Recurrence
- ▶ Earthquakes and their Socio-economic Consequences
- ▶ ESI2007 Intensity Scale for Assessing Earthquake Intensities
- ▶ Landscapes, Paleoseismic
- ▶ Mechanisms of Earthquakes in Aegean
- ▶ Paleoseismology
- ▶ Paleoseismology: Integration with Seismic Hazard
- ▶ Post-earthquake Diagnosis of Building Structures
- ▶ Propabilistich Seismic Hazard Analysis
- ▶ Seismic Analysis of Masonry Buildings: Numerical Modeling
- ▶ Seismic Analysis of Masonry Infilled Concrete Buildings: Numerical Modeling

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